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Analogical understanding of the Ragone plot and a new categorization of energy devices

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Abstract

The main function of energy devices is to generate power and store energy. The typical storage devices are battery and capacitor; generation devices are internal combustion engine (ICE), gas turbine, and fuel cell. Every kinds of energy devices can be compared together in the Ragone plot with respect to specific energy and specific power. Moreover, some difficulties to make position of solar cell in the Ragone plot are proposed. In this paper some analogical explanation is given to understand the underlined meaning. The barrel model is introduced to make analogy; the specific volume and area to the specific energy and specific power. The relationship between the curves depicted in axises of cell voltage with current and specific energy with specific power is tried to be shown in the viewpoint of device operation conditions. Also, the limitation of the Ragone plot is discussed to encompass the existing energy devices to be utilized as the standard benchmarking chart.

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Keywords: Ragone plot; Energy device comparison; Specific energy; Specific power; Barrel model;

1. What is the Ragone plot?

Due to increasing energy consumption and environmental hazardous, the efficient and clean energy sources are urgently required in modern society. Thus, energy devices such as battery, fuel cell, solar cell, geo-thermal, and wind turbine are developed; also, their performance have been enhanced extremely. In addition, hybridization of two or more of them is seriously considered by many groups. The Ragone plot is a famous guide line for energy devices. The Ragone plot named by David V. Ragone has been

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originally used for the purpose of comparison among battery performance. [1, 2] Also, it is useful tool for comparing energy devices such as fuel cell, internal combustion engine, etc. [3, 4]

The Ragone plot clearly shows limitation and direction of energy devices development. The new developed batteries should be placed on the Ragone plot to higher position toward normal axis which refers high energy density. The point which represents fuel cell has to move right side of the Ragone plot which refers increasing power density. Even if the Ragone plot clearly and systematically expresses the guide line of energy device development, there are several problems for requiring enhancement. First, the Ragone plot cannot express all energy devices such as solar cell and wind turbine. Second, the plot cannot follow modern technology development. Thus, more accurate and extensive plot is urgently required for devoting energy device development.

1.1. Analogical understanding of the Ragone plot

For plotting the Ragone plot, the characteristics of devices have to be fully understandable such as energy density and power density of devices. Also, the ratio of energy and power density tells the characteristic of each energy device. So, devices, which are included in the same category, are followed the same slope. However, it is very difficult to intuitively understand the slope which is relationship between energy and power density. It can be simply understandable using simple analogy such as water barrel as shown in figure 1(a). In this analogy, the size of barrel and opening size of barrel are represent the energy density and power density of energy devices.

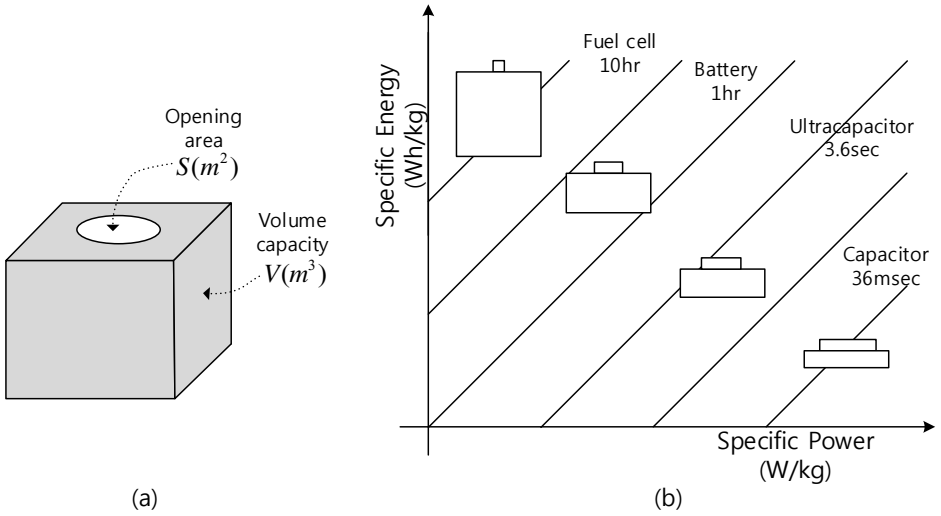

Fig. 1. (a) Barrel model for energy devices; (b) Specific area and specific volume plot

$$specific\ area = S/m(m^2/kg) \tag{1}$$

$$specific\ volume = V/m(m^3/kg) \tag{2}$$

Specific area is defined as the ratio of opening and mass of barrel as shown in equation (1). And, specific volume is defined as the ratio of barrel volume and mass of volume as shown in equation (2). The specific area and volume are corresponding power density and energy density respectively. The ultra-capacitors (super-capacitors) can deliver very high power but the storage capacity is very limited. It can be expressed the barrel which has large specific area and small specific volume. The ratio of the specific area and specific volume are constant for all batteries as shown in figure 1(b). Fuel cells can store large

amounts of energy but have a relatively low power output. It can be expressed that the barrel has small specific area and large specific volume. For all fuel cell, the ratio between the specific area and specific volume are same as shown in figure 1(b). So, for all energy devices are explained by the barrel model which expresses energy device as ratio of specific area and specific volume.

2. Device Operation Effects on the Ragone Plot

The Ragone plot might project physical properties of devices as ratio of energy density and power density. In electrochemical devices, the characteristic of devices appears in current, voltage, and resistance. So, their characteristic curves might have any relationship with Ragone plot. Figure 2 illustrates the I-V characteristic curves of fuel cell and battery.

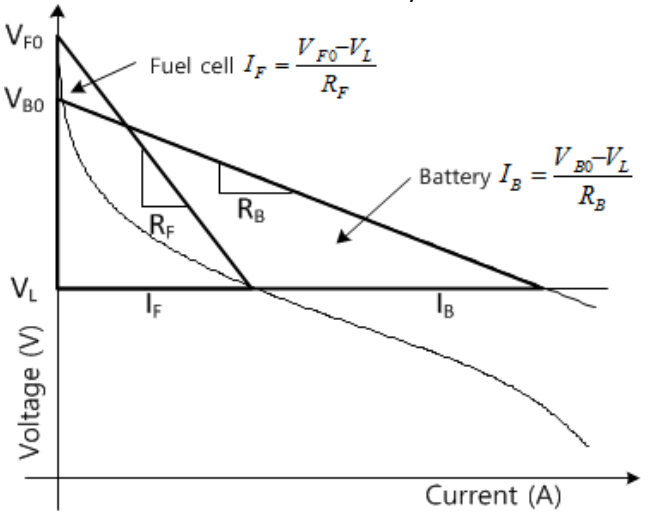

Fig. 2. Triangular shapes of battery and fuel cell

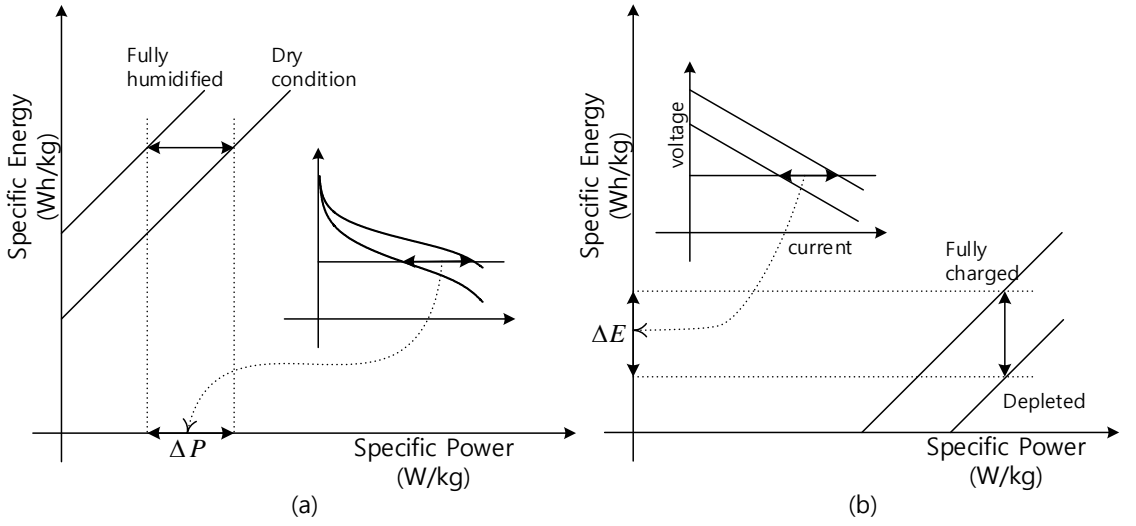

Fig. 3. (a) Specific power variation in fuel cell; (b) Specific energy variation in battery

Each triangles represent relationship of resistance and voltage of each device. In common sense, voltage or potential of device might be have any connection with energy density and resistance might have any connection with power density of device. So, the area of angles might be represent intrinsic properties of devices and it should be expressed on the Ragone plot.

Figure 3(a) and 3(b) illustrate how device operating can give effect on the Ragone plot. In some electrochemical, their physical properties seems be changed by operating condition. For instance, a slop of fuel cell polarization curve, which is refers electro-chemical reaction in the device, varies depending on the relative humidity changing. It refers that the device's resistance changes. I assumed that the resistance of the device is connected to the power density in the Ragone plot. So, the resistance changing induces the power density changing. If the internal resistance of fuel cell changes, then power density changes following power density axis as shown in Figure 3(a). In batteries, their potential changes depending on the state of charge. The potential might be related with the energy density. Thus, when the potential of batteries changes, the energy density of batteries changes along with the specific energy axis as shown in Figure 3(b).

3. New Categorization Beyond the Ragone Plot

The Ragone plot is commonly used for developing guide line and predicting future devices. However, it has a several weaknesses. First, the Ragone plot cannot include all energy devices. Measuring energy density of some devices is very difficult such as solar cell and wind turbine because it seems that they have unlimited and unformed energy. Second, the slope (time line) in the Ragone plot does not well represent energy device's development because the Ragone plot is only considered gravimetric energy density. Volumetric energy density must be considered because by development of material, there exists light material with same volume. So, the Ragone plot cannot show the ultra-capacitor's development. [5] Third, the Ragone plots are only one measure of device; they do not show other important properties, such as the device’s cycle lifetime, energy efficiency, self-discharge, temperature range of operation, or cost. They may also provide misleading information for flow and semisolid batteries, where energy and power densities are decoupled.

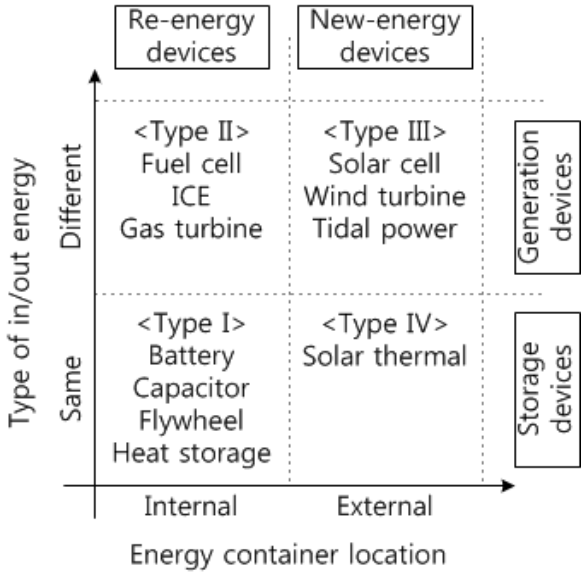

Fig. 4. New categorization chart for energy devices

Even if many disadvantages, the Ragone plot is still a useful tool for energy device development. Thus, the Ragone plot must be compensated by many ways. For this, novel categorization of energy devices is required. Figure 6 illustrates a new concept of energy device categorization. Energy devices can be categorized based on inlet and outlet energy difference and energy container type. There are four types by combination of inlet and outlet energy difference and energy container as shown in Figure 4.

4. Summary

The Ragone plot is widely used for energy device's development for comparing, combining, and predicting for future devices. The Ragone plot provides intuitive and systematic information of devices. However, the Ragone plot has inborn disadvantages and they must be compensated. The barrel model is introduced to understand performance of energy devices and the ratio of specific power and energy relation. A new categorization for every types of energy devices are included in the same one chart to be compared to each other.

Acknowledgements

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